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Economic analysis of hybrid photovoltaic–diesel–battery power systems for residential loads in hot regions—A step to clean future

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Abstract

The growing concerns of global warming and depleting oil/gas reserves have made it inevitable to seek energy from renewable energy resources. Many nations are embarking on introduction of clean/renewable solar energy for displacement of oil-produced energy. Moreover, solar photovoltaic (PV)–diesel hybrid power generation system technology is an emerging energy option since it promises great deal of challenges and opportunities for developed and developing countries. The Kingdom of Saudi Arabia (K.S.A) being enriched with higher level of solar radiation, is a prospective candidate for deployment of solar PV systems. Literature indicates that commercial/residential buildings in K.S.A. consume about 10–45% of the total electric energy generated. The aim of this study is to analyze long-term solar radiation data of Dhahran (East-Coast, K.S.A.) to assess the techno-economic feasibility of utilizing hybrid PV–diesel–battery power systems to meet the load of a typical residential building (with annual electrical energy demand of 35,120 kWh). The monthly average daily solar global radiation ranges from 3.61 to 7.96 kwh/m^2. National Renewable Energy Laboratory's (NREL) Hybrid Optimization Model for Electric Renewable (HOMER) software has been employed to carry out the present study. The simulation results indicate that for a hybrid system composed of 4 kWp PV system together with 10 kW diesel system and a battery storage of 3 h of autonomy (equivalent to 3 h of average load), the PV penetration is 22%. The cost of generating energy (COE, US$/kWh) from the above hybrid system has been found to be 0.179 $/kWh (assuming diesel fuel price of 0.1$/l). The study exhibits that for a given hybrid configuration, the operational

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hours of diesel generators decrease with increase in PV capacity. The investigation also examines the effect of PV/battery penetration on COE, operational hours of diesel gensets for a given hybrid system. Concurrently, attention is focussed on un-met load, excess electricity generation, fuel savings and reduction in carbon emissions (for different scenarios such as PV–diesel without storage, PV–diesel with storage, as compared to diesel-only situation), COE of different hybrid systems, cost of PV–diesel–battery systems, etc.

Keywords: Solar irradiance; PV modules; Residential loads; Battery; Diesel generators; Carbon emissions

Contents

1. Introduction

Due to rapid escalation in world's population and development, fossil fuel (oil/gas) is extensively used for power generation. Over dependence on fixed/limited fossil fuels for large-scale electricity generation is very alarming. Hence, exploitation of renewable sources of energy is imperative to mitigate energy crisis and eventually to subside environmental degradation (due to burning of fossil fuels) in foreseeable future. The Kingdom of Saudi Arabia's (K.S.A.) total installed electricity generation capacity has increased significantly (from 1141 MW in 1975 to 27,000 MW in 2002; also the peak demand is expected to be 59,000 MW in 2020) during the last two decades [1,2]. In particular, Dhahran's peak electricity demand has escalated from 7317 MW in 1995 to 8332 MW in 2001 [3,4]. The above increase can be attributed to rapid growth in residential, commercial, and industrial sectors. Literature reveals that commercial/residential buildings in Saudi Arabia consume 10–45% of the total electric energy consumed [1]. Increased rate of electric energy consumption constitutes one of the biggest problems being encountered by the electric companies in the K.S.A. In order to cope with the increasing electricity consumption trends, it is desirable to explore every possible avenue for generating more energy [4]. One of the options to overcome this profound energy issue is by exploitation of indispensable renewable sources of energy such as solar energy [5]. Since K.S.A. is blessed with high solar radiation levels, an appreciable portion of its energy needs may be harnessed from solar energy. Solar radiation intensities of geographically different provinces of Kingdom are presented in Table 1. However, the present work (as a case study) concentrates on Dhahran.

Solar energy is one of the sustainable/potential/in-exhaustible, site-dependent, benign/nature-friendly (does not produce emissions that contribute to greenhouse effect) source of

Table 1
Monthly average daily global solar radiation (W h/m^2) of different provinces (major cities) of the Kingdom of Saudi Arabia

Province (City)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual avg.
Eastern (Dhahran)	3790	4612	5430	6456	7323	7960	7559	7160	6512	5378	4273	3615	5839
Western (Taif)	4444	5163	5575	5819	5810	6396	6266	5929	5532	5233	4594	4383	5429
Northern (Qurayat)	3464	4736	5486	6421	7095	7418	7514	6936	6077	4741	3804	3027	5562
Southern (Abha)	4372	5275	6083	6025	6527	6459	5746	5985	6197	6433	5923	4853	5824
Central (Riyadh)	3526	4578	5073	5480	5641	6140	6125	5881	5707	5286	4503	3639	5132

Note: Data of eastern province represents average of the period 1986–1993 (*Source*: Meteorological Station, Research Institute, Dhahran).
Data of other provinces represents average of the period 1971–1980 (*Ref*.: Saudi Arabian Solar Radiation Atlas, Riyadh, Saudi Arabia, 1983).

renewable energy options that is being pursued by a number of countries with monthly average daily solar radiation level in the range of 3–6 kWh/m^2, in an effort to reduce their dependence on fossil-based non-renewable fuels [6–13]. Solar collectors can be classified as either solar thermal energy converters or solar electric energy converters. Devices that directly convert solar into electric energy are generally called photovoltaics (PVs) [11]. The concept of PV is well understood and currently thousands of PV-based power systems are being deployed worldwide, for providing power to small, remote, grid-independent/de-centralized applications [6]. Additionally, use of renewable/solar energy reduces combustion of fossil fuels and the consequent CO_2 emmision which is the principal cause of global warming. Global warming is expected to change terrain and climate of many countries unless measures are taken [14–17]. More importantly, in the light of December 1997s Kyoto's protocol on climate change (due to carbon emissions), about 160 nations have reached a first ever agreement (to turn to renewable/wind/PV power) to limit/cut carbon emissions. Although, solar energy is enormous, but PV driven power system is still an expensive option (PV system capital cost is about 4000 $/kW, capital cost of conventional power systems is about 1000 $/kW) [18]. The high initial investment cost of PV systems poses to be the main barrier/pressing-factor/road-block that hampers promotion of this technology in large-scale. Nonetheless, PV finds application in remote areas (where it is un-economical to extend/stretch the utility grid) which lack access to electric grid [18,19]. PV systems have the advantage of minimum/un-attended maintenance and easy expansion (up-sizing) to meet growing energy needs. PV modularity/expandability (modules are available off-the-shelf) is one of its major strength and it allows the users to tailor PV system capacity to the desired situation. PV systems produce electricity during the times when we demand it most, on hot sunny days coinciding with our peak electricity consuming periods. The demerits are: PV is capital-cost-intensive and its sunshine-dependent output does not match the load on 24 h basis. However, technological breakthroughs (yielding cost reduction of PV, improved efficiency, etc.) may change the situation [10,18].

Despite abundant availability of solar energy, a PV system alone cannot satisfy load on a 24-h basis [18]. Stand-alone diesel gensets (relatively inexpensive to purchase), are generally expensive to operate and maintain especially at partial loads [20]. Often, the

variations of solar energy generation do not match the time distribution of the load. Therefore, power generation systems dictate provision of battery storage facility to narrow-down/smoothen/dampen the time-distribution mismatch between the load and solar energy generation and to facilitate for maintenance/outages of the systems [10,21]. PV-generated electricity stored in batteries can be retrieved during nights. Use of diesel system with PV–battery reduces battery storage requirement. Research conducted worldwide indicates that hybrid PV/diesel/battery system (represents an economically acceptable compromise between the high capital cost of PV autonomous system and high O&M + fuel cost of fossil fuel generators) is a reliable source of electricity [19]. Reliability is one of the main selling feature. Hybrid systems add a new dimension to the time-correlation of intermittent PV sources. PV and diesel have complementary characteristics: capital cost of PV is high as compared to diesel, operating cost of PV is low (relative to diesel), maintenance requirements of PV are less as compared to diesel, diesel energy is available all the time where as availability of PV is highly dependent on solar radiation [19]. The prospects of derivation of power from hybrid systems has gained momentum and a number of PV–diesel–battery installations (with capacity factors in the range of 20–35%) exist around the world [19,22,23]. The cumulative installed capacity of all solar systems around the world passed the landmark figure of 3120 MWp in 2003. The global installed capacity of solar power is expected to reach 207 GWp by 2020 (the cost of solar modules is likely to go down to US$1/W delivered). Also, the projections indicate that by 2020 solar systems can provide energy to over a billion people globally and provide 2.3 million full-time jobs [24].

The research on feasibility of renewable energy systems at Dhahran, has been the subject matter of several earlier studies [25–27]. In the present work, solar radiation data of the period 1986–1993 recorded at the meteorological station, Dhahran (26° 32′N, 50° 13′E) has been analyzed to assess the techno-economic feasibility of utilizing hybrid PV–diesel–battery power systems to meet the load requirements of a typical residential building/house (with annual electrical energy demand of 35,120 kWh). Load influences the power system design markedly. The hybrid systems considered in the analysis comprise of different combinations of PV modules/arrays supplemented by battery storage and diesel gensets. Specifically, the merit of hybrid PV–diesel–battery system has been evaluated with regards to its size, operational requirements, cost, etc. National Renewable Energy Laboratory's (NREL) Hybrid Optimization Model for Electric Renewable (HOMER) software has been used to carry out the techno-economic feasibility (analysis and dimensioning) of hybrid power systems. HOMER is a sophisticated tool or computer model that facilitates design of stand-alone electric power systems [28]. The investigation places emphasis on the impact of PV penetration on energy production, cost of energy, number of operational hours of diesel generators for a given hybrid situation, etc. To gain additional understanding/insight, attention has been focused on un-met load, excess electricity generation, percentage fuel savings and reduction in carbon emissions of different hybrid systems (relative to diesel-only scenario), cost of PV–diesel–battery systems, COE of different hybrid systems, etc.

2. Background information and instrumentation

Climatic conditions dictate the availibility and magnitude of solar energy at a site. Dhahran is located just north of the Tropic of Cancer on the eastern coastal plain of Saudi

Arabia and is nearly 10 km inland from the Arabian Gulf Coast. Although it is in the vicinity of the coast, but is situated in very much a desert environment. Two distinct seasons are noticed in this region: a very hot season (May to October) and a cold season (November–April). Monthly mean temperatures reach close to 37 °C for hot months and in cooler months the mean temperatures drop by about 20 °C as compared to the hot months. The relative humidity exhibits a large diurnal cycle on the order of 60% round the year. Typical long-term annual mean precipitation is about 80 mm. The winds blow from 270° to 360° direction range (north to north-westerly winds) for most of the time during the year [29].

The present study utilizes the data recorded at solar radiation and meteorological station (Research Institute) located at Dhahran. The instruments installed at the station meet the requirements for class 1 sensors according to the classification of the World Meteorological Organization [30,31]. The data is being recorded on hourly basis. The global solar radiation measurements are made using Eppley (model PSP) pyranometer. The station is continuously supervised to clean the sensors and to minimize instrumental problems. The sensors are regularly calibrated against reference sensors (to account for degradation and malfunctioning of sensors) maintained at the station. More details of the station have been reported in Ref. [29].

3. Solar radiation data and operational strategy of hybrid system

Long-term monthly average daily global solar radiation values for Dhahran are plotted in Fig. 1. The irradiation level is high during the summer months (May–August) as compared to other months. The yearly average daily value of the solar radiation is 5.84 kwh/m^2. Fig. 1 shows clearly that the variation in the solar radiation values between the years is minimal. In view of the steady nature of solar radiation (and as a case study) 1993s data has been used for simulations (in HOMER). The energy calculations are made by matching the solar radiation data with the characteristics of PV modules [32]. The characteristics of some of the commercial PV modules are furnished in Table 2. The PV modules which are composed of several solar cells are integrated/clustered in series-parallel arrangement (cells are wired in series to provide greater voltage and in parallel to provide greater current) to form solar arrays. Despite advancements in the state-of-the-art, today's best PV systems can achieve an overall efficiency of about 12 percent [11]. These lower efficiency values may not make this alternative attractive at the moment. However, technological breakthroughs, may change the scenario and pave way for more widespread use of PV systems [10,18].

The schematic of hybrid PV–diesel–battery system is shown in Fig. 2. The dispatch strategy is load following type and interaction between different components is as follows: in normal operation, PV feeds the load demand. The excess energy (the energy above the average hourly demand; if any) from the PV is stored in the battery until full capacity of the battery is reached. The main purpose of introducing battery storage is to import/export energy depending upon the situation. In the event, that the output from PV exceeds the load and the battery's state of charge is maximum, then the excess energy is fed to some dump load or goes un-used (due to lack of demand). A diesel system is brought-on-line at times when PV fails to satisfy the load and when the battery storage is depleted (i.e. when the battery's state of charge is minimum).

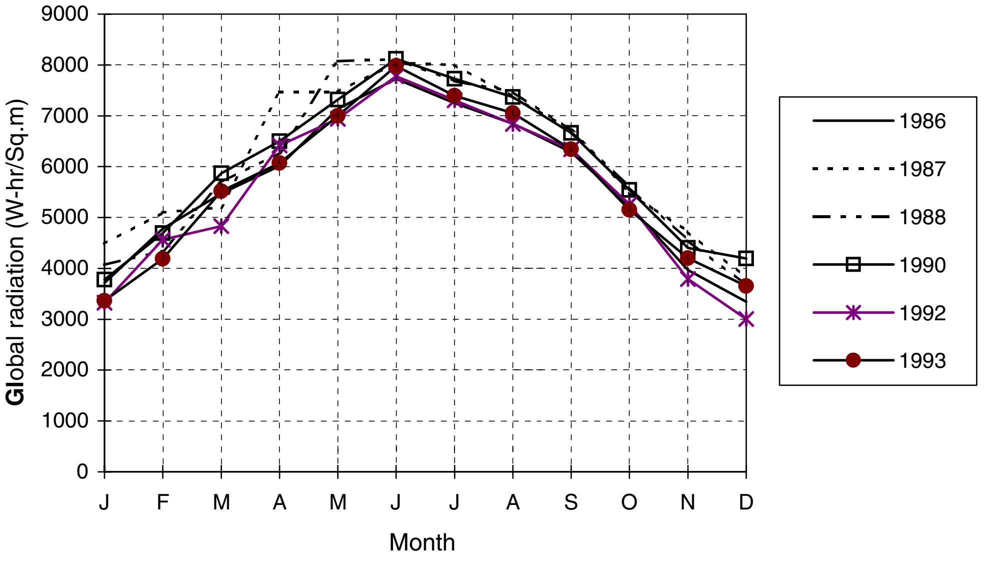


Fig. 1. Monthly average daily global radiation.

Table 2
Characteristics of some commercial PV modules

Module size $L \times W \times D$	Rated power (W), Rp	Current (Å)	Voltage (V)	Module reference η
$1113 \times 502 \times 50$ (mm)	60	3.5	17.1	0.107
$1108 \times 660 \times 50$ (mm)	83	4.85	17.1	0.113
$18.5'' \times 25.7'' \times 2.1''$ (in)	35	2.33	15.0	0.15
$25.2'' \times 25.7'' \times 2.1''$ (in)	50	3.00	16.7	0.15
$34.1'' \times 25.7'' \times 2.2''$ (in)	70	4.14	16.9	0.15
$56.1'' \times 25.7'' \times 2.2''$ (in)	120	7.10	16.9	0.15
$50.8'' \times 39.0'' \times 1.4''$ (in)	167	7.2	23.2	0.15

L: length; *W*: width; *D*: depth.
The above modules are high efficiency solar electric modules and Kyocerasolar modules.
Power specifications are at standard test conditions of: 1000 W/m^2 solar irradiance, 25° cell temperature.

4. Results and discussions

An important consideration of any power generating system is load. As a case study and as a representation of residential buildings, the measured annual average energy consumption (based on 3 years of data) of a typical two bedroom, centrally air-conditioned family house (floor area = 169.8 m^2, located in Dhahran) has been considered as yearly load (35,120 kWh) in the present study [33]. This load could also be a representation of remotely located residential buildings which lack access to the utility grid (even today, there are many communities/settlements living or dwelling in small pockets in remote locations of K.S.A.). The daily average load profile is shown in Fig. 3.

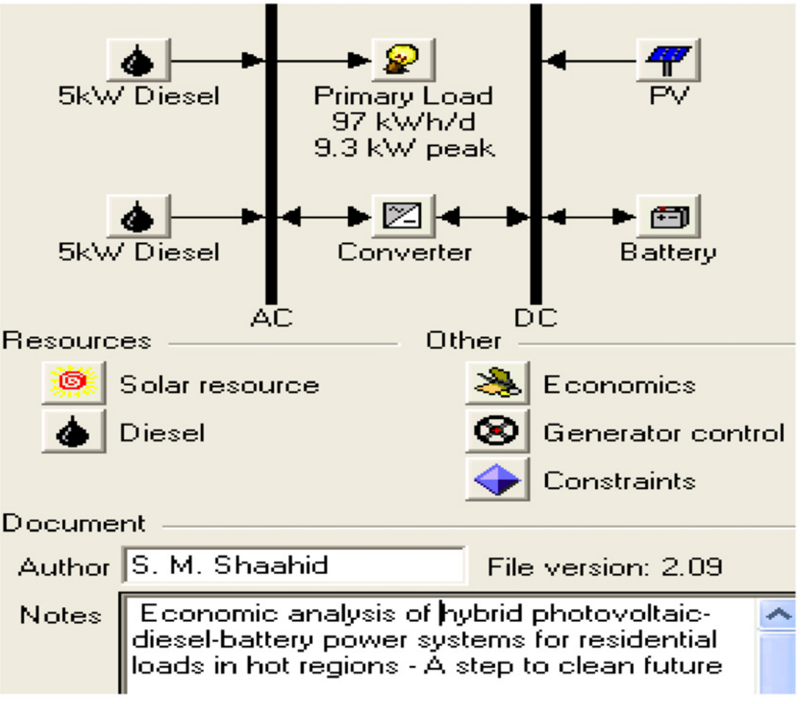


Fig. 2. Schematic of hybrid PV–diesel–battery power system.

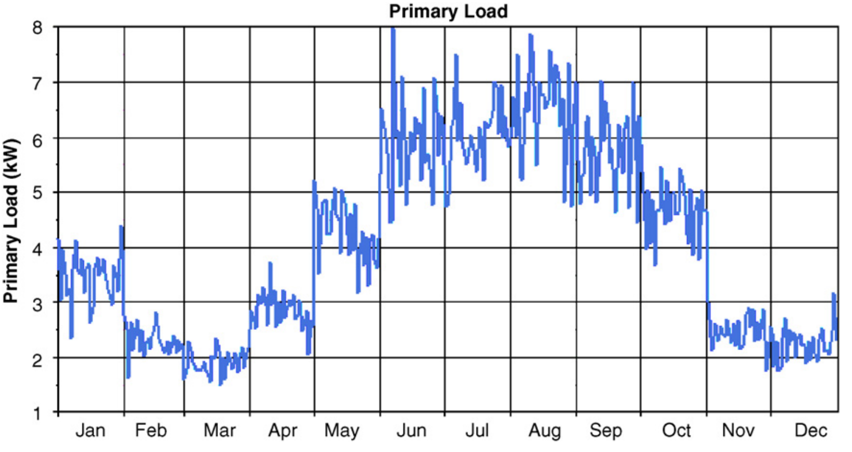


Fig. 3. Daily average load (kW) for a complete year.

As illustrated in this figure, the load seems to peak during June–September. The peak requirements of the load dictate the system size.

In the present work, the selection and sizing/dimensioning of components of hybrid power system has been done using NREL's HOMER software. HOMER is a general-purpose hybrid system design software that facilitates design of electric power systems for stand-alone

applications. Input information to be provided to HOMER includes: electrical loads (one year of load data), renewable resources (e.g. 1 year of solar radiation data), component technical details/costs, constraints, controls, type of dispatch strategy, etc. HOMER designs a optimal power system to serve the desired loads. HOMER is an simplified optimization model/code, which performs hundreds or thousands of hourly simulations over and over (to ensure best possible matching between supply and demand) in order to design the optimum system. It uses life cycle cost to rank order these systems. It offers a powerful user interface and accurate sizing with detailed analysis of the system. The software performs automatic sensitivity analyses to account for the sensitivity of the hybrid system design to key parameters, such as the resource availability or component costs [28].

The hybrid systems simulated consist of different combinations of PV panels/modules supplemented with battery bank and diesel generators. The study explores a suitable mix of inter-dependent dominant/key parameters/variables such as PV array power (kWp), battery storage, and diesel capacity to match the pre-defined load (with 0% capacity shortage). As a rule of thumb, diesel generators are sized to meet the peak demand of the power. The peak demand of the present case study is 9.3 kW as depicted in Fig. 2. In this regard, two diesel generator sets with a combined power of 10 kW (to cover peak load and to cover spinning/operating reserve of about 10% to overcome rapid changes in load) have been considered for carrying out the techno-economic analysis of the hybrid systems. Two diesel gensets (D1, D2) each of 5 kW capacity have been considered. Multiple gensets are used to reduce excess energy. The operating/spinning reserve is surplus electrical generation capacity (over and above that required to cover the load) that is instantly available to serve/cover additional loads. It provides a safety margin that helps ensure reliable electricity supply even if the load were to suddenly increase or the renewable power output were to suddenly decrease.

Several simulations have been made by considering different PV capacities. The PV capacity has been allowed to vary from 0 to 24 kW. The battery storage/bank sizes (kWh) considered include 0–6 load-hours/autonomy (equivalent to 0–6 h of average load, i.e. equivalent to 0–6 Surette batteries with details as listed in Table 3). The study assumptions made for making simulations on HOMER are tabulated in Table 3. As a starting point, simulations have been performed for PV–diesel systems with no storage. The simulation results (*for diesel price of 0.1 US$/l*) are presented in Figs. 4. In Figs. 4, the first column shows the presence of PV modules in hybrid system, second-third column indicate the presence of diesel units, fifth column highlights size/capacity (kW) of PV considered in a particular/given case, eleventh column shows cost of energy generation (COE, $US/kWh) of 1 kWh of energy, etc. It can be noticed from these results/figure that in general the PV penetration (renewable energy fraction, column 12) has varied from 0% to 70%. In an isolated system, renewable energy contribution of 70% is considered to be high. Such a system might be very difficult to control while maintaining a stable voltage and frequency. The level of renewable energy fraction in hybrid systems (deployed around the world) is generally in the range of 11–25% [19]. A trade-off/balance needs to be established between different feasible options. The COE from hybrid PV–diesel system (4 kW PV, 10 kW Diesel system, no-storage, 0% annual capacity shortage) with 22% PV fraction has been found to be is 0.178 US$/kWh as shown in Fig. 4. It can be depicted from Fig. 4 that COE increases with increase in penetration of PV.

It is evident from Fig. 4, that as penetration of PV increases, the operational hours of diesel generators decrease which eventually reduce emission of green house gases in the

Table 3
Technical data and study assumptions of PV, diesel units, and batteries

Description	Data
PV	
Capital cost	6900 US$/kW
Life time	25 years
Diesel generator units:	
Rated power of diesel unit 1 [D1]	5 kW
Minimum allowed power (min. load ratio)	30% of rated power
No load fuel consumption	0.42 L/h
Full load fuel consumption	1.65 L/h
Rated power of diesel unit 2 [D2]	5 kW
Minimum allowed power (min. load ratio)	30% of rated power
No load fuel consumption	0.42 L/h
Full load fuel consumption	1.65 L/h
Batteries	
Type of batteries	Surette 6CS25P
Nominal voltage (V)	6 V
Nominal capacity	1156 Ah
State of charge (SOC)	40%
Nominal energy capacity of each battery (V*Ah/1000)	6.94 kWh
Dispatch/operating strategy	Multiple diesel load following
Spinning reserve	
Additional online diesel capacity (to shield against increases in the load or decreases in the PV power output)	10% of the load

atmosphere. It can be noticed that for diesel-only (10 kW) situation, the operational hours of the two diesel units are 8760 and 3534, respectively. However, for PV–diesel hybrid system (4 kW PV, 10 kW diesel system, 0% annual capacity shortage, zero battery storage, as shown in Fig. 4) with 22% PV penetration, the operational hours of the two diesel units are 8632 and 2708, respectively. The operational hours of the two diesel gensets (D1, D2) of hybrid PV–diesel system (with 22% PV fraction) system decreased by 2% and 23% as compered to diesel-only situation. This indicates that introduction of PV panels decreases load on the diesel generators.

For a given PV capacity of 4 kW (together with 10 kW diesel system), the information related to energy generated by PV and diesel systems, excess electricity, unmet load (kWh), capacity shortage (kWh) and the cost break-down of PV–diesel power systems is presented in Figs. 5 and 6. It can be seen from Fig. 5 that with the above system configuration, un-met load is 0 kWh and excess energy of about 5% is generated. It should be mentioned over here, that this excess energy produced goes unused due to lack of demand (sometimes it is fed to dump loads). Fig. 5 indicates that the monthly average hybrid PV–diesel generated power is high during summer months (May–August) as compared to other months. This is a favorable characteristic because electricity demand is high during the summer months in K.S.A. HOMER hybrid model indicates that the total initial capital cost of the hybrid system (4 kW PV, 10 kW diesel, no-storage) is US$ 38,000 while the net present cost (NPC) is US$ 98,911 (Figs. 5 and 6). It can be noticed from (Fig. 6) that the initial capital cost of

PV (kW)	D5 (kW)	Dsl (kW)	Conv. (kW)	Total Capital	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	D5 (hrs)	Dsl (hrs)
	5	5		$ 5,000	$ 71,397	0.129	0.00	13,902	8,760	3,534
4	5	5	6	$ 38,000	$ 98,911	0.178	0.22	12,088	8,632	2,708
4	5	5	12	$ 43,400	$ 105,256	0.190	0.22	12,088	8,632	2,708
4	5	5	18	$ 48,800	$ 111,602	0.201	0.22	12,088	8,632	2,708
4	5	5	24	$ 54,200	$ 117,947	0.213	0.22	12,088	8,632	2,708
8	5	5	6	$ 65,600	$ 119,165	0.215	0.39	10,590	7,784	2,250
8	5	5	12	$ 71,000	$ 125,509	0.226	0.39	10,589	7,784	2,250
8	5	5	18	$ 76,400	$ 131,854	0.238	0.39	10,589	7,784	2,250
8	5	5	24	$ 81,800	$ 138,199	0.249	0.39	10,589	7,784	2,250
12	5	5	6	$ 93,200	$ 142,363	0.257	0.51	9,770	7,144	2,084
12	5	5	12	$ 98,600	$ 147,920	0.267	0.51	9,646	6,991	2,084
12	5	5	18	$ 104,000	$ 154,265	0.278	0.51	9,646	6,991	2,084
12	5	5	24	$ 109,400	$ 160,611	0.290	0.51	9,646	6,991	2,084
16	5	5	6	$ 120,800	$ 167,605	0.302	0.59	9,331	6,798	1,996
16	5	5	12	$ 126,200	$ 171,780	0.310	0.60	8,987	6,370	1,996
16	5	5	18	$ 131,600	$ 178,126	0.321	0.60	8,987	6,370	1,996
16	5	5	24	$ 137,000	$ 184,471	0.333	0.60	8,987	6,370	1,996
20	5	5	6	$ 148,400	$ 193,799	0.350	0.65	9,069	6,590	1,944
20	5	5	12	$ 153,800	$ 197,272	0.356	0.66	8,616	6,025	1,944
20	5	5	18	$ 159,200	$ 203,617	0.367	0.66	8,616	6,025	1,944
20	5	5	24	$ 164,600	$ 209,962	0.379	0.66	8,616	6,025	1,944
24	5	5	6	$ 176,000	$ 220,431	0.398	0.69	8,890	6,450	1,905
24	5	5	12	$ 181,400	$ 223,450	0.403	0.70	8,367	5,797	1,905
24	5	5	18	$ 186,800	$ 229,795	0.415	0.70	8,367	5,797	1,905
24	5	5	24	$ 192,200	$ 236,140	0.426	0.70	8,367	5,797	1,905

Fig. 4. Technical and economic parameters of PV–diesel systems.

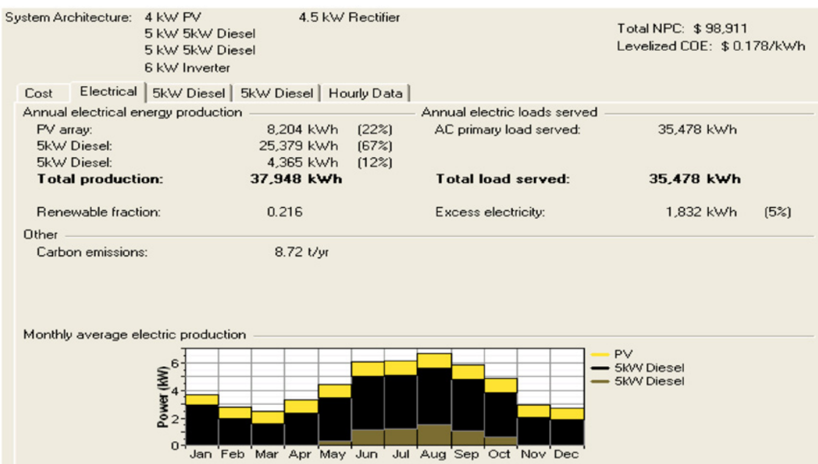
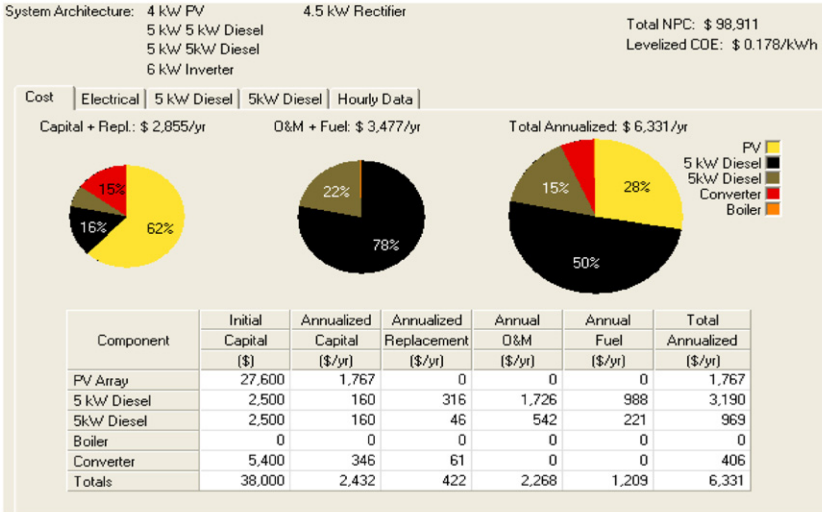


Fig. 5. Power generated by photovoltaic and diesel systems.

PV system is about 70% of the total initial capital cost. This highlights that initial cost of PV system in hybrid system is predominant. However, annual operation and maintenance cost of PV/converter system, is 0% of the total O and M + fuel cost.



Component	Initial Capital ($)	Annualized Capital ($/yr)	Annualized Replacement ($/yr)	Annual O&M ($/yr)	Annual Fuel ($/yr)	Total Annualized ($/yr)
PV Array	27,600	1,767	0	0	0	1,767
5 kW Diesel	2,500	160	316	1,726	988	3,190
5kW Diesel	2,500	160	46	542	221	969
Boiler	0	0	0	0	0	0
Converter	5,400	346	61	0	0	406
Totals	38,000	2,432	422	2,268	1,209	6,331

Fig. 6. Cost of photovoltaic and diesel power systems.

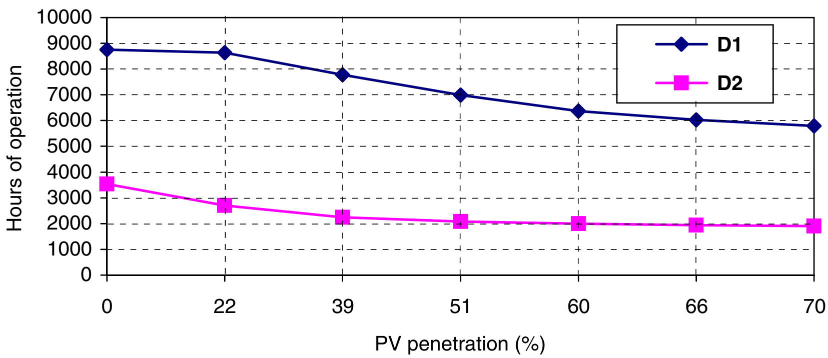


Fig. 7. Impact of PV penetration on diesel engine operaion.

The percentage fuel savings by using hybrid system (4 kW PV, 10 kW diesel system) as compared to the diesel only situation is about 14% as shown in Fig. 4. Moreover, percentage fuel savings increases by increasing the PV capacity. The diesel fuel savings may only be quantifiable by justifying the additional capital expenditure invested in PV. It has also been observed (Fig. 5) that the percentage decrease in carbon emissions with 22% PV fraction is about 13% as compared to diesel-only (zero % PV energy) case. The effect of PV penetration on diesel operation time, diesel fuel consumption, carbon emissions, excess energy generation, etc. has been demonstrated in Figs. 7–9.

As a final remark, attempt has been made to evaluate the benefits of association of short-term storage (with PV–diesel systems) in terms of fuel savings, total diesel run time, and excess energy generation relative to no-storage systems. In order to assess the impact of battery storage on a given hybrid system (4 kW PV, 10 kW diesel, 22% PV penetration), battery storage capacity was varied (in simulations) from 0 to 6 load-hours/autonomy

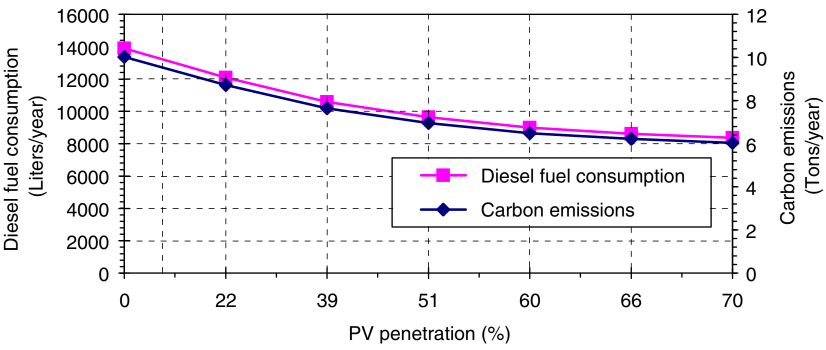


Fig. 8. Impact of PV penetration on diesel fuel consumption and carbon emissions.

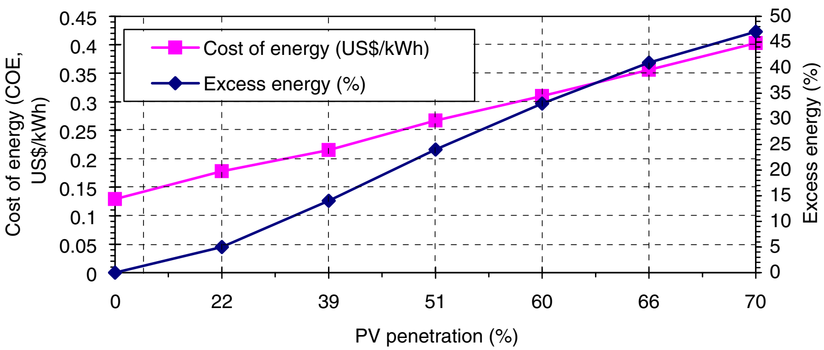


Fig. 9. Impact of PV penetration on COE and excess energy generated.

(equivalent to 0–6 h of average load). The results of the these simulations are presented in Table 4 which demonstrates the effect of battery storage on: operational hours of diesel units, diesel fuel consumption, excess energy generation, carbon emissions, COE, etc. The COE from the above hybrid PV–diesel–battery system (22% PV penetration, with 2% excess energy) with 3 h of autonomy or battery storage has been found to be 0.179 $/kWh (*assuming diesel fuel price of 0.1 $/l*). Literature indicates that COE from PV systems is about 0.20 US$/kWh [34–37]. As mentioned above, percentage fuel savings by using hybrid PV–diesel system 4 kW PV + 10 kW diesel (no-storage) is 14% as compared to diesel-only situation. Expectedly, presence of battery further enhances/elevates the fuel saving potential. The percentage fuel savings for the same PV penetration is 19% (5% more relative to PV–diesel system) with inclusion of 3 h of battery storage. Further increase in storage results in only little economic benefits because of high cost of batteries (i.e. fuel saving is not much for battery storage greater than 3 h of average load). Broadly speaking, maximum benefits of storage (in the present case) can be realized for a battery capacity of 3 h of autonomy. As stated earlier, the percentage decrease in carbon emissions by using hybrid system 4 kW PV + 10 kW diesel (no-storage, 22% PV penetration) as compared to the diesel only scenario is 13%. However, the percentage decrease in carbon emissions for the same PV penetration is 19% (as compared to diesel-only case) with inclusion of 3 h of battery storage. It can be noticed that the COE increases with increase in size of battery

Table 4
Number of operational hours of diesel generators, PV penetration, un-met load, excess energy, annual diesel fuel consumption, cost of energy of hybrid PV-diesel systems (for given PV/diesel capacity, for different sizes of battery storage capacity, based on diesel price of 0.1 US$/l)

Hybrid system (kW)	Battery storage capacity (hours of hourly demand)	Operational hours of different diesel generators		Renewable energy (PV) fraction (% of load)	Un-met load (kWh)	Excess energy (%)	Carbon emissions (tons/year)	Annual diesel fuel consumption l/year	Cost of energy (COE) $/kWh
		D1 (5 kW)	D2 (5 kW)						
0 kW PV + 10 kW diesel	0	8760	3534	0	0	0	10.03	13,902	0.129
4 kW PV + 10 kW diesel	0	8632	2708	22	0	5	8.72	12,088	0.178
	1	8196	1950	22	0	3	8.24	11,423	0.172
	2	8105	1883	22	0	3	8.17	11,322	0.175
	3	8104	1856	22	0	2	8.16	11,309	0.179
	4	8104	1831	22	0	2	8.15	11,298	0.182
	5	8104	1803	22	0	2	8.14	11,286	0.186
	6	8104	1783	22	0	2	8.14	11,277	0.190

storage. Also, the operational hours (diesel run time) of the diesel units in PV–diesel system further decrease with inclusion of battery storage (Table 4). For example, for the above hybrid PV–diesel (4 kW PV, 10 kW diesel system, 22% PV penetration, no-storage) system, the operational hours of the two diesel gensets (D1, D2) decreased by 2% and 23% as compered to diesel-only situation. However, (for the same configuration) with inclusion of 3 h of battery, the operational hours of the two diesel gensets (D1, D2) decreased by 8% and 48% as compered to diesel-only situation. In addition to the above benefits, inclusion of short-term storage also results in decrease in excess energy. The excess energy is 5% for hybrid PV–diesel (4 kW PV, 10 kW diesel system, 22% PV penetration, no-storage) system. However, (for the same configuration) with inclusion of 3 h of battery, the excess energy is 2% for hybrid PV–diesel–battery scenario. For a given PV capacity, the lower the excess energy the better the economy of the PV–diesel systems.

5. Conclusions and recommendations

In the wake of higher monthly average daily solar global radiation intensity (3.61–7.96 kwh/m^2), the study indicates that Dhahran in particular and K.S.A. in general is a prospective candidate for deployment of PV power systems for residential applications in crisis. The simulation results indicate that for a hybrid system comprising of 4 kW PV system together with 10 kW diesel system and a battery storage of 3 h of autonomy, the PV fraction/penetration is 22%. The cost of generating energy from the above hybrid PV–diesel–battery system has been found to be 0.179 US$/kWh (*assuming diesel fuel price of 0.1 $/l*). The study exhibits that for a given hybrid PV–diesel configuration, the number of operational hours of diesel generators decreases with increase in PV capacity. It has been found that for a given PV–diesel hybrid system, the decrease in diesel run time is further enhanced by inclusion of battery storage. The percentage fuel savings by using hybrid PV–diesel–battery system (4 kW PV, 10 kW diesel system, 3 h storage) is 19% as compared to diesel-only situation. The percentage decrease in carbon emissions by using hybrid system (4 kW PV, 10 kW diesel system, 3 h of battery, with 22% PV fraction) is 19% as compared to the diesel only scenario. More importantly, with use of the above hybrid system, about 2 tons/year of carbon emissions can be avoided entering into the local atmosphere.

The hybrid PV–battery–diesel power system offers several benefits such as: utilization rate of PV generation is high; load can be satisfied in the optimal way; diesel efficiency can be maximised; diesel maintenance can be minimized; reliable power supply; and a reduction in the capacities of PV, diesel and battery (while matching the peak loads) can occur. Also investments in mobilization of PV systems may stimulate/gear up the local economy (in a long-run) by exploitation of available local resources. The present work shows that the potential of solar energy cannot be overlooked. A fraction of Saudi Arabia's energy demand may be harnessed from PV systems. The findings of this investigation can be employed as a frame-of-reference in designing of hybrid PV–diesel–battery systems for other locations having similar climatic and load conditions.

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